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To Mr. F.J. Kee
Director of Research

ORGANIC MEMBRANE SEPARATION PROCESSES: A STATE-OF-THE-ART REVIEW

S.J. Oda

This report reviews the current application of organic membranes in industrial processes by industrial subsector. These 'wise' electrotechnologies, which include reverse osmosis, electrodialysis, ultrafiltration and gas separation, provide significant potential for energy conservation and productivity improvement in each subsector. A summary of application opportunities and research and development needs in membrane technology is presented.

Many industrial processes can be described as simply the separation of one thing from another. For example, in the treatment of sewage and many industrial effluents, separation and concentration of the wastes from the fluid are performed to achieve efficient disposal. Sea water is separated into salt and potable water. Protein and sugars are separated and recovered from food processing effluents. A direct approach to this separation would be to form a barrier that permits molecules of one kind to pass but that excludes all others. Such a barrier can be made from thin films of certain organic polymers. These films or membranes can discriminate between substances on the basis of several properties. In the membrane process called ultrafiltration (UF) molecules are separated on the basis of their size, in electrodialysis (ED) according to their electrical charge and in reverse osmosis (RO) water molecules are separated from dissolved substances.

Membrane separation technologies are new with many commercial applications only available since 1970. Present applications are almost exclusively in water treatment and processing of aqueous streams in the food, medical and pharmaceutical industries. This

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technology holds great promise for performing separations more efficiently and cost effectively than conventional techniques (ie, evaporation, distillation). Candidate applications can be identified in almost every industry in which liquids or gases are separated, consumed, or processed.

From an electrical utility standpoint, electricity is required in membrane processes primarily for pumping fluids. Although these processes represent relatively small loads, they do represent 'wise' applications of electricity that displace conventional thermal techniques and show good economic payback. This has been well illustrated in France at Electricite de France (EdF) where work suggests that, in some cases these separation technologies can use as little as 1% of the energy consumed by conventional distillation/1/.

Two of the strengths that have encouraged the use of membrane processes are its ability to save energy and improve productivity. Energy savings can be accomplished in three ways. Firstly, energy-intensive phase change processes such as distillation and evaporation can be potentially displaced by membranes. Feedstock heating can be eliminated since most membrane processes can be conducted at low or ambient temperatures. Finally, given the development of suitable membrane materials, the use of membranes at elevated process temperatures (>100^{o}C) would allow the conservation of significant amounts of energy.

Productivity can be improved by the use of membrane technology if process and effluent streams can be treated to recover and/or recycle dilute concentrations of unconverted feedstocks, products and chemical additives. For example, reverse osmosis and ultrafiltration are becoming commercial processes in the metal finishing and electroplating industries for the recovery of metals from rinse water. In many cases, the recovery of valuable materials from dilute streams is simply not feasible with other separation technologies. By-products can be recovered and sold. For example, in the food industry effluent streams can be treated by reverse osmosis and ultrafiltration to recover protein and sugars and then sold/2,3/. In addition, membrane treatment of industrial waste waters can relieve the burden on water treatment facilities and eliminate costly haulage charges.

For this review, it is impractical to discuss all of the membrane technologies that have been developed. Liquid, inorganic and biomedical membranes should be the subject of a second report. This report focuses on four of the more widely used polymeric membrane processes: ultrafiltration (UF), reverse osmosis (RO), electrodialysis (ED) and gas separation. Application opportunities are summarized in matrix form according to commercial (C) or laboratory (L) status (see Table 1). Deficiencies in the technology that must be overcome to realize these opportunities are described. The selection of industries

TABLE 1
ORGANIC MEMBRANE PROCESSES:
Existing and Potential Uses

INDUSTRIAL SECTOR

MEMBRANE TECHNOLOGY	FOOD & BEVERAGE					
	Meat Products	Dairy Products	Fruit & Vegetables	Sugar Processing	Grain Processing	Beverages
Reverse Osmosis	-water treatment (C) -protein recovery (L)	-milk conc.(C) -whey process (C)	-juice conc. (C/L) -water treatment (C)	-displace evap. in sugar,salt and protein processes (C/L)	-protein recovery (L) -solvent recovery(L)	-clarification (C) -concentration (C/L) -water treatment (C)
Ultrafiltration		-protein conc. (C) -whole & skim milk concentration (C)	-water treatment (C)	-displace evap. in sugar salt & protein proc(C/L)	-solvent recovery (L)	-deacidification (L) -clarification (C) -recovery & conc. (C/L)
Electrodialysis		-removal of salt and lactic acid (C)		-displace evap. in sugar salt & protein proc(C/L)		-deacidification (L)
Gas Separation						

MEMBRANE TECHNOLOGY	LEATHER & TEXTILE	INDUSTRIAL CHEMICALS	PULP & PAPER	PETROLEUM & COAL	MINING & METALS FABR'N
Reverse Osmosis	-treatment of sizing, de-sizing and dyeing effluents (C/L) -treatment of tanning effluents (C/L) -hot water recycling (L)	-separation of organic chemicals (L) -deionization & sterilization of water (C)	-boiler feedwater (C) -chemical by-product conc. & recovery (C/L)		-boiler feedwater (C) -pollution control (L) -metal recovery (C) -paint recovery (C) -detergent recovery (C) -deionizing water for electronics and electroplating (C)
Ultrafiltration	-treatment of sizing, de-sizing and dyeing effluents (C/L) -treatment of tanning effluents (C/L) -hot water recycling (L)	-ind cooling tower/side-stream softening -org. chemical sep. (L) -alcohol/water sepr. (L) -oxygen enrichment (L) -latex concentration (C)	-ink recovery (C) -water treatment (C) -chemical conc. & recovery (C)	-oily waste water treatment (C/L) -oxygen enrichment (L)	-pollution control (L) -acid mine water (C) -metal recov. (C) -paint,oil & detergent recovery (C) -oxygen enrichment (L) -uranium recovery (L)
Electrodialysis		-membrane cell in chlor-alkali process (C)			-pollution control (L) -water softening (C) -metal recovery (C) -paint,oil,detergent recovery (C)
Gas Separation			-sensible heat recovery (dehumidify exhaust) (L) -solvent recovery (L)	-gas recycle/recovery(L)	-emission control (L)

C - Commercial Process
L - Laboratory or Pilot Plant Process
C/L - Commercial and Laboratory Process

is based on the number of potential opportunities identified in the literature references and in discussion with manufacturers. Industries considered in this review are food and beverage, leather and textile, pulp and paper, hydrocarbon processing (petroleum and coal), mining and metals fabrication and industrial chemical subsectors. The report's appendices contain a discussion of the matrix entries; descriptions of the four membrane separation processes; an outline of membrane separation theory and operation; membrane materials and equipment; and, a list of manufacturers and local suppliers. Table 2 provides estimates of electrical consumption for some commercial membrane processes.

SUMMARY OF APPLICATION OPPORTUNITIES

The application opportunities in Table 1 and Appendix 1 can be classified in three areas:

- displacement of energy-intensive separations
- feedstock and by-product recovery (including process water treatment)
- sensible heat recovery

(i) Displacement of Energy-Intensive Separations

Applications in this area involve food, industrial chemical and metal fabrication industries and displace, partially or totally, separation operations such as distillation and evaporation. It is not necessary to completely displace a conventional separation operation to effect significant energy conservation. For example in evaporation, preconcentration of a process stream from 5 to 10% solids prior to evaporation represents about a 50% energy savings since half of the water is removed.

(ii) Feedstock and By-Product Recovery

In many processes chemicals, unconverted feedstocks and water are lost in effluent streams. Recycle of these materials is usually not practical because conventional separation techniques are too costly when the concentration of the material is low. Recovery of these materials by membrane techniques (RO, UF and ED) can improve productivity and save energy associated with the recovered products. These applications occur in all of the industries discussed. With respect to wastewater treatment, environmental concerns are becoming a requirement with membrane techniques providing a suitable means for both material recovery and water treatment.

(iii) Sensible Heat Recovery

A significant amount of energy is discharged from various processes as sensible heat in effluent streams. Hot process water (70 to 100°C) is discharged when the concentration of chemicals or waste becomes too high. In drying operations, the exhaust air is nearly saturated with water or solvent and cannot be reused, even though it is still hot (80 to 150°C). If these effluent streams were treated at the plant site to produce clean water, the recycle of sensible heat would be possible because the hot water or air could be reused. Recycle of sensible heat is especially attractive in the food, pulp and paper and textile industries.

DEFICIENCIES IN MEMBRANE TECHNOLOGY

As is evident in Table 1, membrane technology has a wide range of possible applications with significant potential for productivity improvement and energy conservation. However, the technology also has several deficiencies that must be overcome in order to encourage the development and expansion of new membrane applications. The deficiencies include:

- limitations imposed by membrane materials ie, manufacturing techniques, instability and inadequate flux and selectivity

- the relatively narrow operating range of reverse osmosis membrane systems, ie, pH 3 to 8 and a maximum operating temperature <35°C

- high membrane system cost ie, costly manufacturing methods and support materials, the amount of membrane required for a particular process, the frequency of membrane replacement

CONCLUSIONS AND RECOMMENDATIONS

Membrane separation processes are 'wise' electrical technologies that can significantly contribute to energy conservation and productivity improvement in a wide range of industrial applications. These applications can be classified as follows:

- displacement of energy-intensive separations in food, chemical and metal processing industries,

- product/by-product recovery in all discussed industries and,

- sensible heat recovery in food, pulp and paper and textile industries

Deficiencies in membrane technology that have limited their expansion into new industrial processes include material instabilities, a relatively narrow range of operating conditions and high system and membrane replacement costs.

Based on the preceding conclusions and the overall impressions gained during the preparation of this review, the following studies are recommended:

1. Criteria for the successful application of membrane technology in Ontario industries should be developed. Using these criteria, new membrane applications should be assessed with a feasibility study and then, if required, in a laboratory demonstration.

2. European experience with organic membrane processes has been very favourable. Contact with the relevant personnel at the Electricity Council (UK), RWE (West Germany) and EdF (France) should be made to determine the status of their programs in membrane technology.

3. Technical currency should be maintained in this field especially with respect to new membrane materials (ie, improved stability in a wider range of operating conditions) that could dramatically expand the application opportunities.

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APPENDIX I

INDUSTRIAL APPLICATIONS OF MEMBRANES

(i) Food and Beverage Subsector

The food and beverage subsector is composed of diverse industries including meat products, dairy products, preserved fruit and vegetables, grain mill products, bakery products, fats and oils, beverages and sugar products. Commercial membrane processes are now available for the dairy industry in skim milk and whey processing.

In the meat products industry, reverse osmosis (RO) and ultrafiltration (UF) may be useful for water treatment and by-product protein recovery/2,3/. Hot water and steam are used in this industry for cleaning and sterilization. On-site reverse osmosis of this effluent water could permit sensible heat recycle and by-product protein recovery. Development of membrane materials that are stable up to 100°C is needed to make hot water treatment possible.

In the dairy industry, reverse osmosis has been used commercially since 1970 for whey processing (salt and sugar concentration/8/. Ultrafiltration of acid and cheese whey is used to concentrate protein and to separate lactose and salts from protein/8/. Whole and skim milk can also be processed by ultrafiltration to concentrate proteins and fats and fractionate water, lactose and salt from the higher molecular weight components. Milk can also be concentrated by reverse osmosis. Commercial installations of these applications are on line in the United States. Difficulties with membrane processing in the dairy industry include membrane fouling, sanitation and physical and/or chemical changes to the product (altering taste and texture). According to the manufacturers of membrane equipment for the dairy industry, these problems have been overcome as indicated by the expanding market for their equipment.

Concentration of juices and sauces by evaporation is a major operation in the processing of fruits and vegetables/9,10,11/. In laboratory and pilot plant studies reverse osmosis has shown a two- to four-fold concentration of various juices. Reverse osmosis and ultrafiltration may also be useful for water treatment in fruit and vegetable processing. In peeling operations, for example, treatment of hot effluent water can allow water, sensible heat and peeling chemicals recycle/3/. Thermal instability of membrane materials, sanitation and fouling are problems that may be encountered in this industry.

Reverse osmosis, ultrafiltration and electrodialysis have the potential to be used in sugar processing, especially for the partial displacement of evaporation of sugars, salts and

proteins. The potential applications have been reviewed/9/. As in other food and beverage industries, developmental studies are required to reduce membrane fouling and thermal instability.

Membrane processes can be used in the recovery of proteins from grains and oils from oil seeds/9/. Combined extraction/membrane separations have been technically feasible and economically attractive. In addition, if membrane materials are developed that are stable in organic solvents, ultrafiltration or reverse osmosis may be useful in displacing conventional distillation for solvent recovery in vegetable processing.

The use of ultrafiltration for beverage clarification and electrodialysis for de-acidification is possible/2/. Water treatment and beverage concentration are also possible with membrane processes.

In 1982 the total energy consumed by the Ontario food industry has been reported as 42.8×10^{12} kJ/12/*. Of this consumption the energy used for drying can be estimated as 6×10^{12} kJ/9/. Perhaps half of this energy was used for evaporation. Membrane processes for concentrating liquids consume roughly one-tenth the energy required by triple effect evaporation for water removal/13/. Assuming only a two-fold concentration by reverse osmosis, approximately 1.5×10^{12} kJ could be saved annually in the food industry. Additional savings could results from hot process water recycling, reduced energy requirements (transportation, heating and cooling) for liquids not usually concentrated (ie, milk), and reduced costs for distillation by providing concentrated feeds (ie, vegetable oils).

(ii) Leather and Textile Subsectors

The potential for application of membrane technology in the leather and textile industries is significant. Treatment of process and effluent waters by reverse osmosis and ultrafiltration in these industries can provide for water, chemical and sensible heat recycle. Energy conservation potential of hot water recycling is important since approximately 50% of the energy consumed in the textile industry is lost in hot effluent discharge/14/. In addition, water treatment by reverse osmosis and ultrafiltration improves pollution control. Chemicals are not released into the environment and hot water recycle decreases thermal pollution.

Membrane technology as demonstrated in laboratory and pilot plant scale projects can be applied for treatment of sizing, desizing and dyeing effluent waters/14/. Similarly, reverse osmosis and ultrafiltration have been investigated in leather tanning applications/14/.

In 1982 Ontario textile and leather industries consumed 14.1×10^{12} kJ. Natural gas and oil account for approximately 75% of

*3600 kJ ≡ 1 kWh

this energy use, primarily as fuel for boilers/12/. Applying US estimates/9/ to Ontario industries, direct recycle of hot water could save up to 3.8 x 10^{12} kJ/yr. With the development of suitable membranes recycle treatment could be economically achieved through membrane technology.

(iii) Industrial Chemical (Inorganic & Organic) Subsectors

Membrane technology is just beginning to emerge in this subsector. One commercial membrane application has been demonstrated in the chlor-alkali industry. Here, membrane cells replacing conventional asbestos diaphragm and mercury cell methods have reduced energy requirements by 10% and alleviated concerns over disposal of waste mercury and asbestos cells/9/. This membrane cell uses an ion specific membrane between charged electrodes and, in the case of the chlor-alkali process, allows only the passage of sodium ions. This effectively improves the overall process efficiency.

Commercial application of membranes to separate organic chemicals has been minimal. This is in spite of the large potential that exists in this subsector to displace conventional distillation processes. (In 1982, distillation accounted for approximately 8.4 x 10^{12} kJ in Ontario's industrial chemical subsector/12/). Although both reverse osmosis and ultrafiltration are capable of separating organic chemicals, some questions remain. These involve the requirements for (a) large membrane areas to provide acceptable separation and, (b) improved stability of membrane materials in the chemical environment. In addition, most of the technical literature has dealt with bench-scale experiments using small, flat membranes. Scaling large industrial systems from this information is virtually impossible. More studies of larger membrane modules using hollow fibre and spiral wound membranes are required to provide better sizing information.

(iv) Pulp and Paper Subsector

In 1982, Ontario pulp and paper industries consumed approximately 87.0 x 10^{12} kJ/12/. Potentially large applications for membrane technology in this subsector are in the treatment of wash waters in pulping, bleach and paper manufacturing/16/. As in the leather and textile industries, plant site water treatment with membrane technology can allow water recycling and chemical and sensible heat recovery as well as improvement in pollution control. An example of chemical recovery is in the sulphite pulping processes. Pilot plant studies have indicated that membrane concentration of chemical by-products from spent sulphite liquor consumes one-eighth the energy when compared to conventional evaporation/9/. The United States pulp and paper industry consumes approximately 6% of its energy in sulphite pulping. Assuming comparable consumption in Ontario, up to 5.2 x 10^{12} kJ could be saved if all sulphite processes were converted to by-product recovery with membranes. In addition, treatment of

effluent water by membrane processes could represent a significant source of energy conservation and productivity improvement.

With respect to sensible heat recovery, pilot plant studies have indicated that membranes (cellulose acetates and polyamides) can be used to remove water vapour from a paper dryer exhaust system/17/. This would permit the recycle of dry hot air back to the dryer. The preliminary analysis shows that the membrane system is 13 times more efficient than conventional vacuum pumping.

(v) Petroleum and Coal Subsector

Petroleum and coal industries (ie, hydrocarbon processing) accounted for approximately 4% of the total energy consumed in Ontario's industrial sector in 1982. This is equivalent to 22 x 10^{12} kJ. The two major applications for membranes in these industries are waste water treatment and gas separations. A by-product of hydrocarbon processing is waste water which is often contaminated with oils and requires cleaning by energy-intensive distillation or air flotation. Ultrafiltration methods have been used to treat oily waste waters to levels comparable to conventional methods; however, without data on waste water discharge it is difficult to estimate energy savings potential.

With respect to gas separations, petroleum refining processes yield gaseous by-products (ie, hydrogen, hydrogen sulphide, carbon dioxide, natural and synthetic gases) which, if efficiently separated, with membrane processes could be recycled for higher production yields or sold as feedstocks or by-product fuels to other industries. An assessment of the energy value of these by-products is required to obtain an estimate of the savings that could result from using membrane separation techniques.

(vi) Mining and Metals Fabrication Subsectors

Membrane processes for these subsectors are under development, although some applications are in widespread commercial use in the fabricated metal products industry.

In the mining industry (metal and non-metal), reverse osmosis, ultrafiltration and electrodialysis are being studied as a means of pollution control for effluent streams and for metal recovery/18,19/. In the fabricated metal products industry, ultrafiltration and to a lesser extent reverse osmosis and electrodialysis are used commercially for the recovery and concentration of protective coatings for metal parts, oil emulsions from rinse waters, detergents used in cleaning metal working machine parts and metals from plating bath rinse waters. In this respect, one interesting concept involves the potential re-use of chromium plating wastes by other industries/20/.

Industries such as chrome pigment and leather tanning could use plating wastewaters if adequately concentrated by reverse osmosis. This illustrates another example of the 'wise' use of an electrotechnology that can reclaim industrial wastes for sale to an unrelated industry.

The total energy consumed by these industries in Ontario has been estimated to be approximately 137 x 10^{12} kJ/yr./12. Much of the energy in mining is consumed as electricity for operating machinery and as heat for smelting. Because of the nature of energy use and the developmental state of membrane processes in these industries, the potential energy savings by using membranes is difficult to determine.

APPENDIX II

DESCRIPTION OF MEMBRANE SEPARATION PROCESSES

The basic concept of membrane separation processes is illustrated in Figure 1. Membrane separation techniques are driven primarily by differences in pressure, concentration and electric field across the membrane and can be differentiated according to type of driving force, the molecular size of the separated material or the type of operation. The following descriptions of the processes are given in these terms. Appendix III and the literature/4,5,6,7/ provide additional information on membrane theory and operation.

(i) Reverse Osmosis (RO)

Reverse osmosis is one of the best-developed membrane separation processes and is used for the purification of solutions. In reverse osmosis, a purified liquid is produced by separation from the feed solution, which contains dissolved solids (ie, low molecular salts) or other liquids (see Figure 2). The driving force in reverse osmosis is the difference between the applied pressure and the osmotic pressure across the membrane. The cost of pumps and excessive membrane degradation usually limits the applied pressure to about 1000 psi. Reverse osmosis membrane materials have been predominantly cellulose-based acetates with a maximum temperature limit of 30^{o}C and a pH range of 3 to 8. Current research has developed polyamide and polysulphone membranes which can be used at higher temperatures (60^{o}C) in a wider range of pH environments (1-10). These membranes are used in a variety of configurations ranging from the expensive plate-and-frame systems through the spiral wound ("jelly roll") systems to tubular and hollow fibre systems (see Figure 3). Each system development provides a more compact and inexpensive way of getting the large required area of membrane into a modular package.

(ii) Ultrafiltration (UF)

Ultrafiltration equipment is similar in appearance to reverse osmosis but separations are somewhat more coarse. In essence, it is molecular filtration: it removes microscopic particles and large dissolved molecules from a solution by filtration. Using 'looser' membranes, ultrafiltration systems operate at low pressures (10-100 psi) as compared to the 400 psi pressures required by the 'tight' reverse osmosis membranes. In addition, membrane materials can be made from a wider range of polymers that have greater chemical resistance and higher operating temperatures than reverse osmosis membranes. Ultrafiltration membranes are available in the same type of system configurations as reverse osmosis.

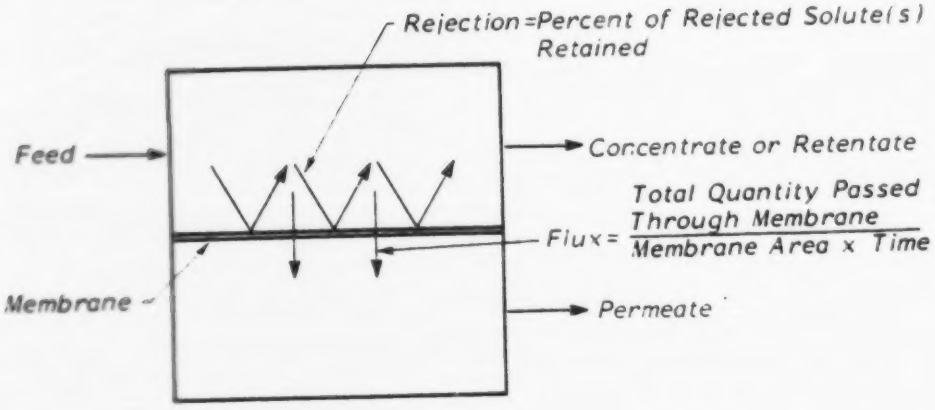


FIGURE 1

BASIC CONCEPT OF MEMBRANE SEPARATION PROCESSES /9/

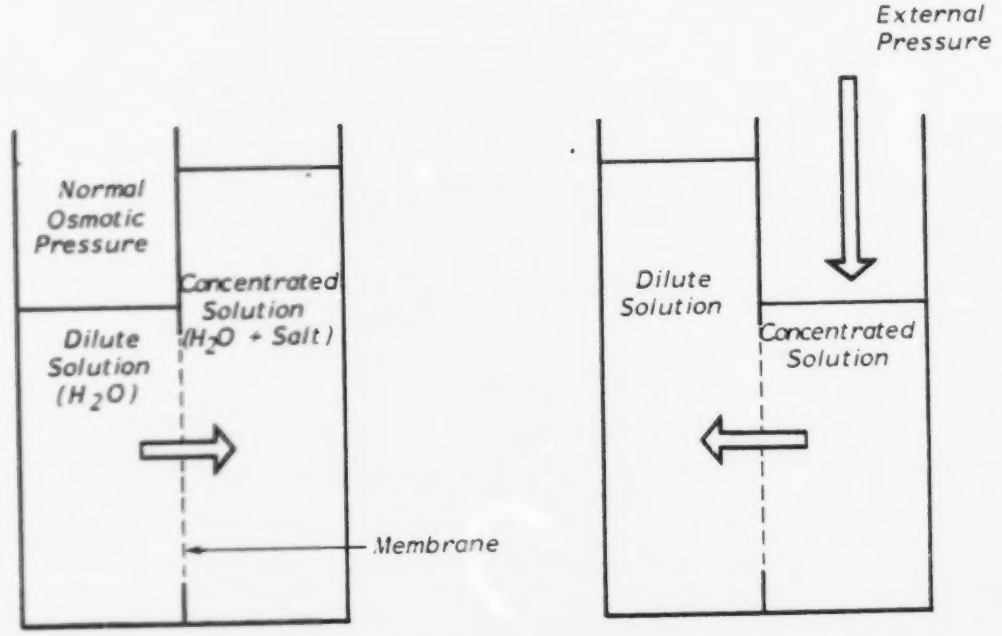


FIGURE 2

OSMOTIC PHENOMENA AND REVERSE OSMOSIS

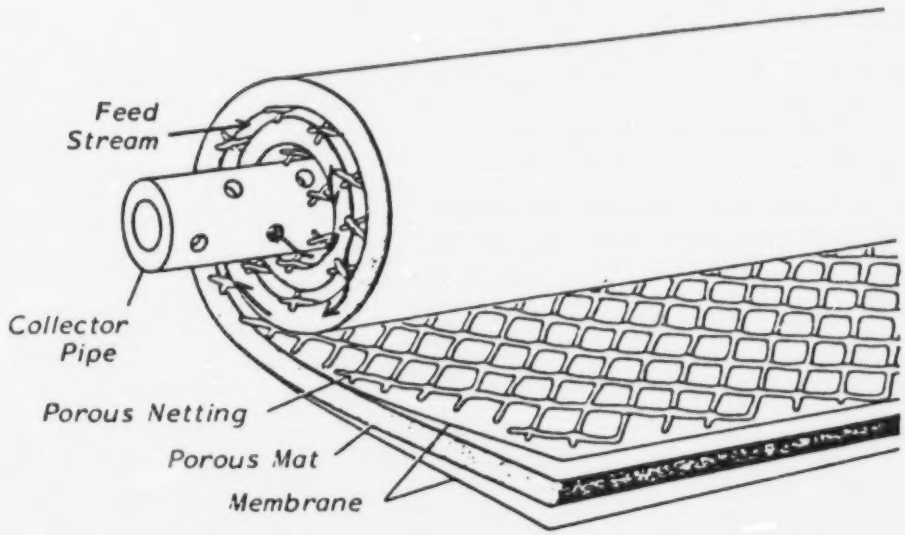
(iii) Electrodialysis (ED)

The driving force for reverse osmosis and ultrafiltration is the pressure difference. In electrodialysis, the driving force is provided by an electric field applied across a membrane or a set of membranes (see Figure 4). Electrodialysis membranes are selectively permeable to those ions bearing either a positive or negative charge. In an electrodialysis cell, membranes of alternating polarity are arranged in a stack and an electric field is applied across the entire stack. The result is a concentration of positive and negative ions in alternating cavities of the stack. Electrodialysis membranes are made from the same material as ultrafiltration membranes with comparable temperature and chemical resistances.

(iv) Gas Separation

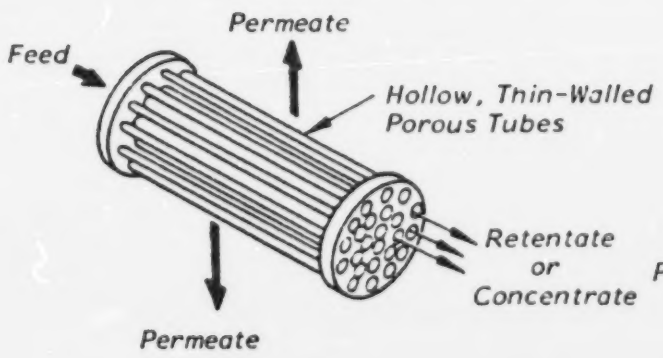
The difference in permeability of organic membranes to different gases can serve as the basis for separating components of a gaseous mixture. The driving force in gas separation can be provided by either a concentration or pressure difference across the membrane. Gas membrane systems like reverse osmosis and ultrafiltration can be composed of various organic polymers in plate-and-frame, spiral-wound and hollow fibre configurations/2,4/.

Table 2 gives some examples of existing industrial applications of reverse osmosis, ultrafiltration and electrodialysis with estimates of their electrical energy consumption.



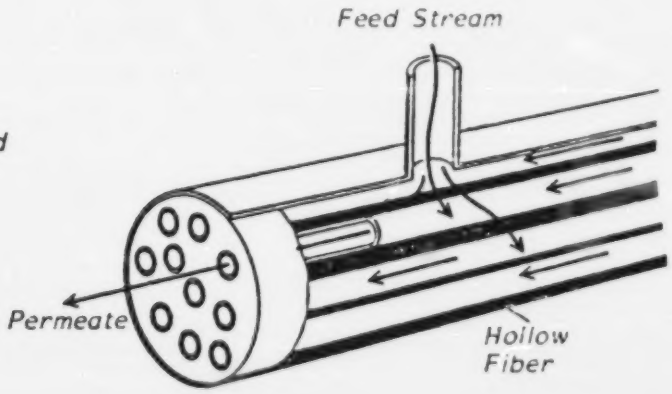
(a) Spiral Wound

(Two membranes separated by a porous mat are wound with a plastic netting around a porous pipe. The feed enters the space provided by the netting and the permeate after crossing the membranes spirals through the mat to the pipe at the centre of the "jelly roll".)



(b) Tubular

(Porous tubes have membranes on the inside or outside surface depending on the direction of flow.)



(c) Hollow Fibre

(Membranes are spun into hollow fibres with inside diameters of 40 micrometer. Fibres are bundled and the feed is pumped around them with permeate flowing out the ends of the fibres.

FIGURE 3

ORGANIC MEMBRANE CONFIGURATIONS

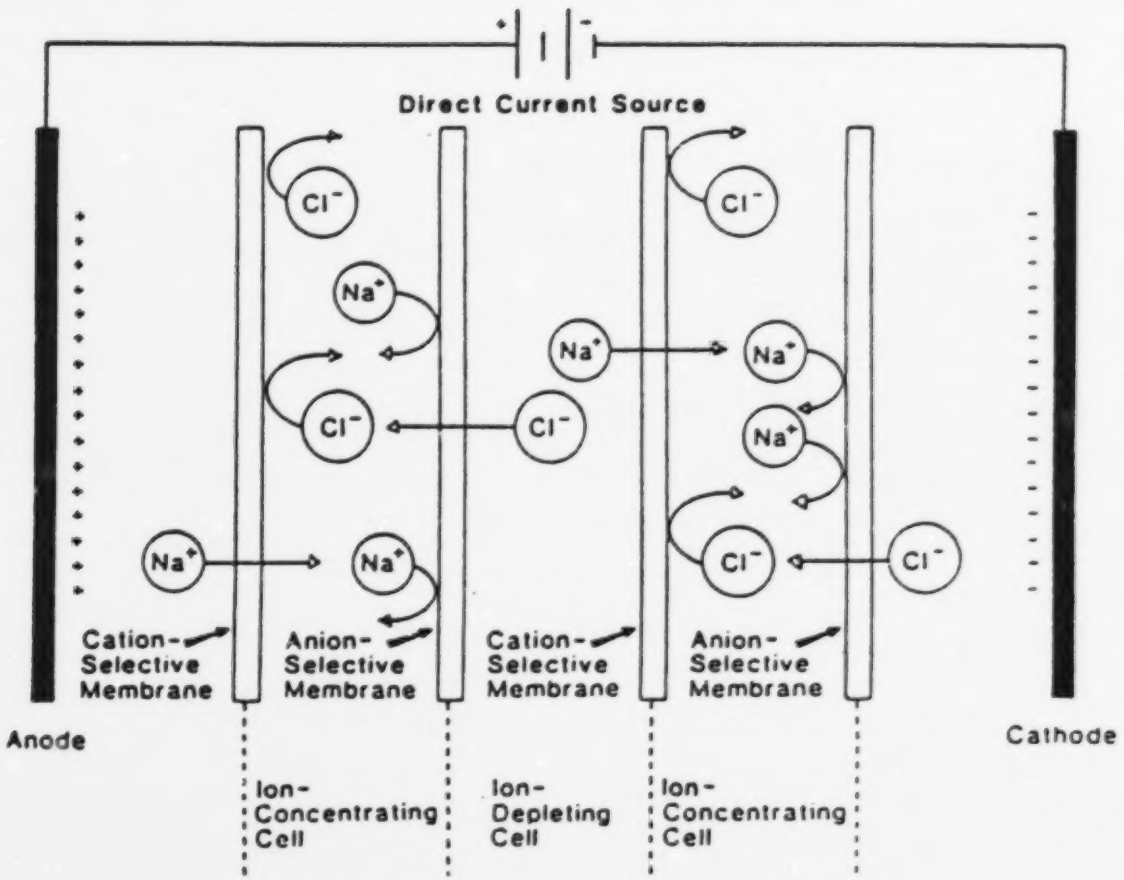


FIGURE 4

BASIC ELECTRODIALYSIS SYSTEM

(In a practical ED unit, a hundred or more membrane pairs are used in the stack.)

167573 RD

TABLE 2

Electrical Energy Consumption Estimates
for Commercial Membrane Processes

Application	Membrane Process	Electricity Consumption	Reference
Juice Concentration	RO	70 kWh/1000 gal	10
Whey Concentration (6 to 21% solids)	RO	25 kWh/1000 gal	23
Whey Concentration (5 to 24% solids)	RO	45 kWh/1000 gal	23
Reverse Osmosis	(general)	1-15 kWh/1000 gal	pvt comm A. Golomb
Desalination	ED	15 kWh/1000 gal	21
Desalination	ED	7 kWh/1000 gal	1
Whey Demineralization	ED	5 kWh/1000 gal	21
Juice Sweetening	ED	200 kWh/1000 gal	21
Salt Production	ED	300 kWh/ton of salt	5
Metal Recovery	ED	15-30 kWh/lb of metal recovered	22
Ultrafiltration	(general)	1 kWh/1000 gal	21
Hard Water Treatment	UF	1 kWh/1000 gal	23
Coffee Concentration	UF	50 kWh/100 gal	22

APPENDIX III

Membrane Theory and Operation

(i) Definition of a Membrane

In membrane technology, a membrane is a thin barrier that separates two fluids and permits selective transport of solutes (dissolved substances) from one fluid to the other fluid. Frequently called a 'semi-permeable' membrane, these materials can be polymeric, metallic, ceramic, a layer of chemicals or even a liquid or gas.

(ii) Concept of Membrane Separation

In order to effect mass transport through the membrane, a driving force (ie, pressure, concentration, electric field) must be applied across the membrane. Under the influence of this driving force, the membrane permits specific components (the solutes, solvents or gases) to pass through (permeate) it. The membrane also inhibits transport of some components. This selective transport forms the basis of the membrane separation process, which generally involves the separation of solutes from a fluid, or the separation of two fluids. The membrane mass transport mechanism is called permeation and can be described in basic terms using the following equation (derived from Fick's law and Henry's law):

$$J = P \times (DF/l)$$

where J = flux expressed as quantity of fluid per unit time per unit of membrane area

P = permeability of membrane

DF = driving force across the membrane

l = membrane thickness

Flux is the bulk fluid transport rate and has units of quantity of fluid per unit time per unit membrane area (eg, $kg/m^{2}*day$). Permeability is the mass transfer coefficient for the specific component, for a group of components or for the bulk fluid and is expressed as quantity of component times membrane thickness per unit of membrane area per unit of driving force.

Two terms are generally used to describe the separation capability of a membrane system: selectivity and rejection. Selectivity is generally defined as the ratio of component permeabilities. Rejection describes membrane separation

capability and is a measure of how well the membrane prevents permeation of the concentrated component(s) into the product stream.

(iii) Membrane Operation

Membrane performance generally changes with time. Performance change is due to several factors including fouling and physical/chemical changes in the membrane (ie, compaction and degradation). These phenomena usually cause a decrease in membrane flux and selectivity and, therefore must be understood in order to develop methods to overcome the resulting adverse effects and establish reliable system performance.

(iv) Membrane Materials

Various materials can be used for the membrane barrier layer including organic polymers (most common), inorganic materials (eg, metals, ceramics, inorganic polymers), liquids and gases. Due to the wide variety of membrane process applications, membranes with a wide range of properties and performance characteristics are required. Some of the principal considerations for membranes selection are separation capabilities (selectivity and rejection), separation rate (flux), chemical and mechanical stability (compatibility with operating environment) and membrane material cost. Common requirements for membranes, regardless of the separation process, are high flux and selectivity, chemical resistance and durability (longest possible life). These properties are determined by the type of membrane material and the fabrication method used in manufacturing.

(v) Systems Equipment

For industrial process the type of membrane system used depends on a number of factors:

- type of separation
- throughput
- process flexibility requirements
- ease of maintenance
- ease of operation

As illustrated in Figure 3 there are three basic types of membrane modules currently being used in industry:

- plate-and-frame
- spiral would
- tube-and-shell
- hollow fibre

APPENDIX IV

Membrane Manufacturers and Local Suppliers

	Manufacturers	Membranes/Membrane Systems	Local Suppliers
1.	Osmonics, Inc Minnetonka, MN	RO, UF	Pelmar Engineering Toronto
2.	Bend Research, Inc Bend, OR	RO, UF	-
3.	Paterson Candy Int Laverstoke Mill, UK	RO, UF	WHE Process Systems Ltd Toronto
4.	Pasilac, Inc Minneapolis, MN	RO, UF	Firing Industries Ltd St. Catherines, Ontario
5.	UOP, Inc Des Plaines, IL	RO, UF, GS	-
6.	Ionics, Inc Watertown, MA	Liquid membranes (research), ED	-
7.	MTR, Inc Menlo Park, CA	Gas separation (research)	-
8.	Film Tec Corp Minneapolis, MN	RO (research)	-
9.	Abcor, Inc Wilmington, MA	RO, UF	APV Crepaco Toronto
10.	Memtek Corp Ottawa, Ontario	RO, UF	-
11.	Permutit Co, Inc Paramus, NJ	RO, UF	-
12.	Monsanto Co Research Triangle Park, NC	Gas separation	-
13.	Dupont De Nemours Co, Inc Wilmington, DL	Gas separation, ED	-
14.	Separex Corp Tyler, TX	Gas separation	-
15.	Fluor Corp Irvine, CA	Gas separation	-
16.	Ionac Birmingham, NJ	ED	-